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Improved Fire Protection for Underground Fuel Storage and Fuel Transfer Areas

By William H. Pomroy and Guy A. Johnson

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere
°F	degree Fahrenheit
fpm	foot per minute
ft	foot
gal	gallon
gpm	gallon per minute
gpm/sq ft	gallon per minute per square foot
h	hour
in	inch
lb	pound
lbf	pound (force)
lbf/s	pound (force) per second
mg/L	milligram per liter
min	minute
pct	percent
pct/yr	percent per year
ppm	parts per million
psi	pound per square inch
s	second
sq ft	square foot
V	volt
V dc	volt, direct current
yr	year
W	watt
wt pct	weight percent

IMPROVED FIRE PROTECTION FOR UNDERGROUND FUEL STORAGE AND FUEL TRANSFER AREAS

By William H. Pomroy[1] and Guy A. Johnson[1]

ABSTRACT

The potential for large-scale fires in underground fuel storage and fuel transfer areas prompted the Bureau of Mines to study fire hazards in these areas and devise improved fire safety technology for use in these areas. This report describes the Bureau's research to characterize and quantify fire hazards in fuel storage and fuel transfer areas, develop guidelines for safe and efficient fueling system design, prepare specifications for automatic fire sensing and suppression systems for these areas, test prototype systems in the laboratory and in underground mines, and perform cost-effectiveness evaluations of the devised technology.

INTRODUCTION

From the early 1950's through the mid-1960's, underground mining was revolutionized by the introduction of mobile rubber-tired diesel-powered equipment. Entirely new and highly productive mining systems were developed based on the concept of "trackless" mining. The increasing use of trackless equipment, however, was accompanied by an increasing frequency of diesel equipment fires. Fires involving rubber, oil, hydraulic fluid, grease, and diesel fuel increased 557 pct from the 1950–64 period to the 1965–79 period. Mobile equipment was involved in less than 10 pct of all underground metal and nonmetal mine fires from 1950 to 1967 but was involved in about 40 pct of all such fires from 1968 to 1979. In response to this growing hazard, the Bureau initiated a research program aimed at improving fire protection technology for underground metal and nonmetal trackless mining operations. The Bureau's research to develop automatic fire protection systems for underground mobile equipment is described in Information Circular 8954.[2]

In addition to fire hazards on vehicles, mobile equipment servicing facilities such as underground shops, maintenance bays, and fuel storage and transfer areas also present a significant fire hazard. These areas are characterized by the presence of combustible materials such as lubricating oils, greases, starting fluids, solvents, hydraulic oils, and diesel fuel; ignition sources such as hot engine surfaces and electrical, cutting, and welding equipment; and constant vehicular traffic. Fuel storage areas, which provide bulk storage in both tanks and drums, and transfer areas, where vehicle refueling takes place, are particularly critical because of their potential for the involvement of very large quantities of diesel fuel, lubricating oils, and hydraulic fluids in a fast-growing, high-energy fire.

Although no large-scale fires in underground fuel storage or transfer areas have yet been reported, the potential seriousness of such fires prompted the Bureau to embark on research to upgrade the overall level of fire safety technology for these areas. The research began with a comprehensive fire hazards analysis. The results of this analysis were then used to establish (1) guidelines for the design of safe and efficient underground fuel storage and transfer areas and (2) specifications for automatic fire sensing and suppression systems for fueling areas. Prototype fire sensing and suppression equipment was fabricated, then laboratory and field tested. All work was accomplished under a contract with the Ansul Co. of Marinette, WI.[3]

ANALYSIS OF FUELING SYSTEM FIRE HAZARDS

Guidelines for the construction of safe fuel storage and transfer areas and design specifications for fire protection systems for these areas were based on data acquired through a comprehensive and detailed analysis of fueling area fire hazards. Data sources included Bureau experts and experts employed by the Mine Safety and Health Administration

[1]Supervisory mining engineer, Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.

[2]Johnson, G. A. Automatic Fire Protection for Mobile Underground Mining Equipment. BuMines IC 8954, 1983, 12 pp.

[3]Ansul Co. Improved Fire Protection System for Underground Fueling Areas (contract H0262023). Volume 1: BuMines OFR 120-78, 1977, 325 pp.; NTIS PB 288 298/AS. Volume 2: BuMines OFR 160-82, 1981, 111 pp.; NTIS PB 83 114744.

(MSHA); private consultants; management, safety, and maintenance personnel from several underground mines; equipment manufacturers; and insurance industry representatives. In addition, researchers visited 16 underground mines to observe fuel storage and transfer area designs and safety practices.

METHODOLOGY

Although the designs of existing fuel storage and transfer areas are based on the unique experiences of their designers and the specific needs of individual mining operations, certain features were common to many of the systems observed. These features, or subsystems, are listed below.

1. Surface storage
2. Surface transport
3. Shaft transport
4. Borehole transport
5. Transport to underground storage
6. Underground storage
7. Transport to fuel transfer area
8. Fuel transfer

An expert panel was convened to rank the hazard associated with each subsystem. The panel consisted of (1) an experienced mine fire hazards analyst who had visited six of the mines in the study, (2) an experienced mine fire hazards analyst who had visited all of the mines in the study, (3) a mining engineering consultant, (4) a petroleum systems design consultant, and (5) a hydraulic systems research and design specialist.

The panel evaluated the eight generic subsystems listed above as well as the design of each system, subsystem, and major component observed at the 16 mines studied. The fire hazard of each subsystem was evaluated in terms of (1) leak or spill potential and (2) ignition potential. Potential sources of leaks and/or spills and potential ignition sources were identified and ranked by each panel member. The individual rankings were averaged to yield overall hazard rankings for each leak or spill and ignition source. The potential range of hazard rankings was from 1 (most hazardous) to 13 (least hazardous).

RESULTS

Results of the analysis of the potential for fuel leaks and spills are shown in table 1.

The three components most likely to leak or cause a spill are the hose to the vehicle, the pump to the vehicle, and the piping to the vehicle fueling pump. All three of these components are situated in the fuel transfer area. Shaft and haulageway piping follow as the next most hazardous components in terms of leaks and spills.

Results of the analysis of the potential ignition sources are shown in table 2.

Six of the thirteen ignition sources identified, including the three most hazardous sources, occur in the fuel transfer area.

A hazard index reflecting the relative fire hazardousness of each fueling subsystem was derived by combining the leak and spill and ignition potential rankings. Hazard indexes for the eight generic fueling subsystems are shown in table 3 in decending order of hazardousness.

As might be expected from the analysis of leak and spill and ignition source potentials, the fuel transfer area was judged to be the most hazardous. Both the probability of a fuel spill and the probability of ignition are highest in this area. Underground fuel storage was ranked as the second most hazardous subsystems. However, although the likelihood of a fire occurring in the storage area is less (than in the fuel transfer area), the magnitude of a fire in the storage area would be far greater.

Fuel transfer areas where fuel tanks and drums are present are more hazardous than areas where only a fueling nozzle is present. The panel agreed that the most likely underlying cause of a fire is operator error, including such unsafe practices as smoking while refueling, overfilling fuel tanks, insufficient precautions during welding in the refueling area, unsafe or careless operation of vehicles, and failure to properly maintain and inspect vehicles and/or refueling equipment.

TABLE 1. — Hazard ranking of potential leak and spill sources

Fueling system component	Hazard ranking[1]
Hose to vehicle	2.3
Underground pump to vehicle	4.5
Piping to fueling pump	5.1
Shaft piping valves	6.5
Haulageway piping	6.7
Haulageway valves	6.8
Surface transfer pump	7.0
Shaft piping	7.1
Underground storage tanks	7.3
Surface storage tanks	8.3
Surface piping	8.4
Haulageway pumps	8.5
Nozzles	12.8

[1]1 = most hazardous; 13 = least hazardous.

TABLE 2. — Hazard ranking of potential ignition sources

Source	Hazard ranking[1]
Electrical sparks from vehicle	2.2
Vehicle engine heat	2.6
Electrical sparks from refueling area	3.6
Smoking	4.4
Impact sparks (from vehicle-rib impacts)	5.3
Welding	7.5
Vehicle exhaust	8.6
Human error	8.6
Hot hydraulic pumps	8.6
Drive shaft brakes	8.7
Unusual occurrences	8.7
Trash build-up	8.8
Spontaneous combustion	8.8

[1]1 = most hazardous; 13 = least hazardous.

TABLE 3. — Fueling subsystem hazard indexes

Subsystem	Index[1]
Fuel transfer area	278
Underground storage area	217
Surface storage area	101
Shaft transport	77
Surface transport	59
Borehole transport	50
Transport to fuel transfer area	48
Transport to underground storage area	43

[1]Highest values indicate most hazardous subsystems.

GUIDELINES FOR SAFE FUELING SYSTEM DESIGN

Fueling system designs should be aimed at mitigating the conditions identified in the hazards analysis as contributing to the occurrence or severity of fueling system fires. Designs that require a minimum of operator skill are preferred because their use can help minimize operator error. Designs that physically separate the vehicles being refueled from the fuel storage area are preferred because they minimize contact between the fuel source and the ignition source. Designs that limit line pressures and have a low risk of tank overfilling are preferred because three features can help minimize leaks and spills. The recommended fueling system design is shown in figure 1, and the design features illustrated in this figure are discussed in the next two sections.

FUEL STORAGE AREA

Surface storage tanks should be designed and constructed in accordance with applicable industry standards. Combustible liquids should not be pumped underground from a large storage tank; instead they should be pumped from a batch tank with less capacity than the underground tank being filled. Borehole transport is preferred over shaft transport. Exhaust from the fuel storage area should be directed to a return. Automatic fire sensing and suppression systems (which are discussed in detail in the next main section of this report) are recommended, as are hand portable fire extinguishers.

A major concern in underground fueling system design is whether to use a wet or a dry transfer line between surface storage and the underground location. A wet line, with fuel in it at all times is advantageous because it makes underground storage of fuel unnecessary. A dry line, used to periodically resupply underground tanks, has the advantage of placing far less stress on piping and fittings. A hazards analysis indicated that the overall hazard was generally slightly less with the dry-line system; however, both systems are acceptable. When choosing between wet and dry transfer lines, local conditions such as type of piping used, length of drop, length of horizontal pipe run from borehole to fuel storage and/or transfer area, frequency of fuel transfers, and the design and layout of the fuel storage and transfer areas should be considered.

Underground storage areas should be fully enclosed and constructed of materials having a fire resistance rating of at least 2 h. Windows should close automatically with fusible links, and the door should remain closed when not in use. The floor should be impermeable (rock or concrete) and have a sump for holding spilled fuel. Lights and wiring should be explosion proof.

The tanks should be of good quality and supported on concrete saddles. An overflow vent pipe large enough to release fuel at the maximum possible delivery rate is recommended to avoid rupture during a possible overfill. This vent should also release pressure in the event of a fire. The overflow vent should feed into an overflow tank equipped with an alarm. Tanks should have a float or sight glass with the refill level clearly marked to reduce human error.

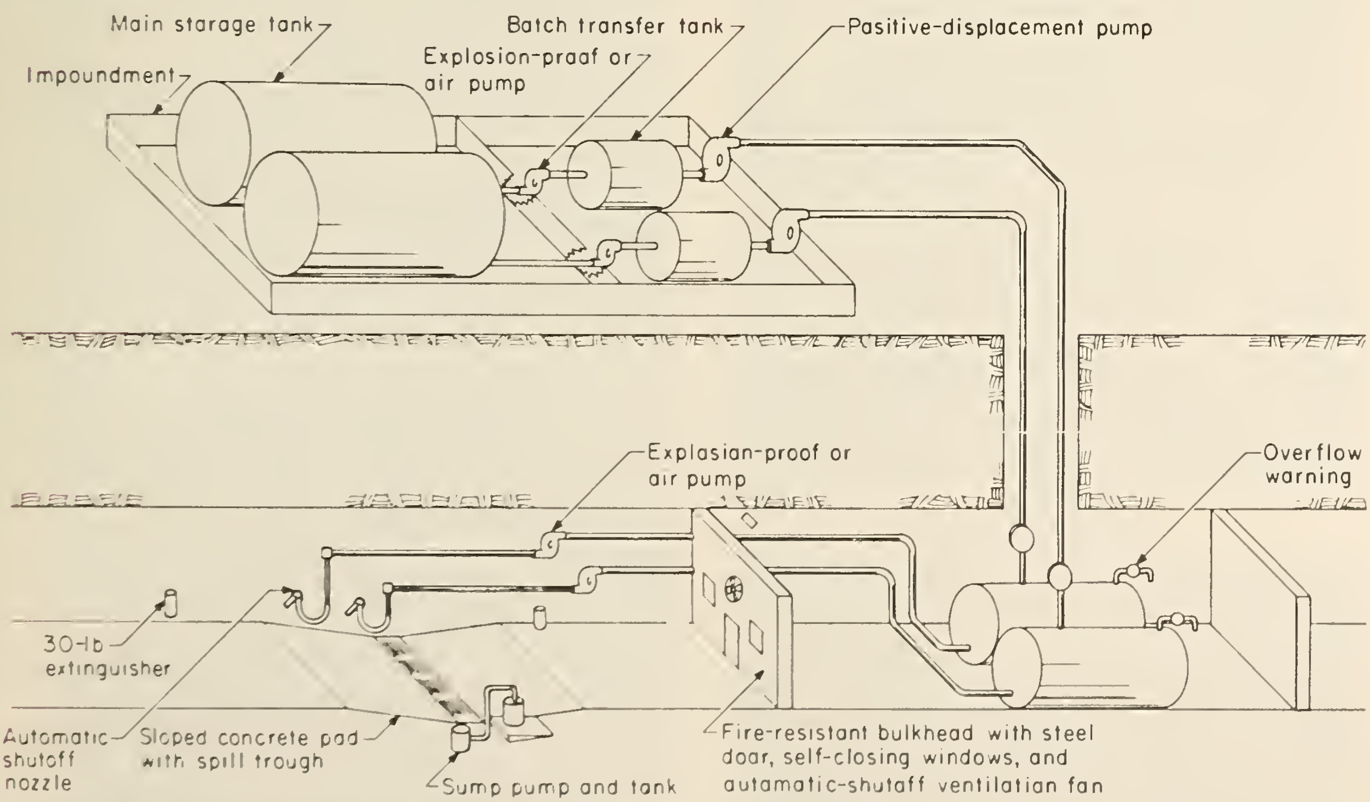

FIGURE 1.—Recommended fueling system design (fuel storage area, top and lower right, and fuel transfer area, lower left; fire sensing and suppression system not shown).

FUEL TRANSFER AREA

There should be no fuel or oil tanks or drums within 50 ft of the fuel transfer area (by shortest accessible route) unless such tanks or drums are enclosed in a fire-resistant structure. Emergency pump controls should be located so they can be quickly reached in the event of fire. The area should be well lighted with explosion-proof lamps. As was recommended for fuel storage areas, exhaust from the fuel transfer area should be directed to a return. Again, automatic fire sensing and suppression systems and hand portable fire extinguishers are also recommended.

Diking or some other form of drainage control should be provided to collect spilled fuel into a container with minimum surface area. A means for absorbing spilled fuel should be located near the nozzles. Fuel transfer areas should not be located where spills would drain toward an underground storage area or shop.

Pumps should be located outside the underground storage area to remove that potential ignition source from the stored fuel. The pump should not keep constant pressure in the fuel lines; it should instead be actuated by the operator during the fueling operation. Automatic shutoff nozzles are recommended to reduce the incidence of overfills. An excess-flow valve should be installed downstream of the pump. The area should be kept as clean and orderly as possible.

DISCUSSION

The preceding guidelines for safe fueling system design represent an optimum rather than a minimum approach. They are based on certain assumptions regarding aspects of mine design that are considered commonplace in the North American metal and nonmetal mining industry. Alternative systems and subsystem elements may result in the same or a higher level of safety depending on local conditions. As examples, the transport of fuel in portable tanks instead of fixed piping is warranted in adit mines, and fuel storage and fuel transfer areas situated near an exhaust shaft and ventilated directly to the return need not be enclosed or protected by suppression systems.

GENERIC FIRE SENSING AND SUPPRESSION SYSTEM

DESIGN CONCEPTS

The development of generic fire sensing and suppression system design concepts was guided by the analysis of fueling system fire hazards. Designs were developed for the fuel transfer area and the underground storage area, which were ranked as the first and second most hazardous fueling subsystems (table 3).

Many different fire suppression systems are currently used to protect underground fuel transfer and storage areas against fires. Due to the many variations in fueling systems designs, no single fire suppression system can be recommended for all applications. Each hazard requires its own analysis and a design concept developed to specifically address that hazard. However, certain general principles of fire protection, such as the suitability of suppressant agents on various fuels and the properties of various detection devices, apply regardless of the hazard under consideration. Therefore, these general principles were applied together with the guidelines for safe fueling system design to develop the generic design concepts for fueling area fire protection systems. The resultant design concepts are discussed in the following sections in the context of these principles and guidelines.

Fuel Transfer Area

The generic fuel transfer area fire protection system consists of three elements: suppression, controls, and detection.

Suppression

Five suppressants were considered for possible use in the fuel transfer area fire suppression system: aqueous film-forming foam (AFFF), water, high-expansion foam, Halon 1301[4] halogenated fire extinguishing agent, and multipurpose dry chemical. Agents eliminated from consideration included carbon dioxide and Halon 1211, because of possible safety hazards to personnel who might be exposed to the agents in a confined area; protein and synthetic foams because they are incompatible with dry chemical, require special air-aspirating equipment, have limited stability, and require higher discharge rates than AFFF; and ordinary dry chemicals because they are unable to extinguish ordinary combustibles such as paper, rags, and wood.

A tradeoff study of the capabilities and limitations of the five suppressants was conducted. Based on this study, no single suppressant emerged as having optimum fire extinguishing capabilities in all possible situations. The selection of a suppressant for a particular application is influenced by all of the following factors: fueling area design, enclosure integrity, physical dimensions, and location in the mine; airflow and air velocity through the area; types of fires expected; and possible effects on personnel. The factor that has the greatest impact on suppressant effectiveness is ventilation. In completely enclosed areas with no ventilation, AFFF, high-expansion foam, and Halon 1301 can be used to effectively extinguish a typical combustible-liquid spill fire and secure the fuel against reignition. However, under the conditions of moderate-to-high ventilation, which are typical of most fuel transfer areas, only AFFF can extinguish and secure a spill fire.

Another important factor influencing suppressant selection is the type of fire expected. In addition to spill fires, combustible-liquid pressure fires and running-fuel fires, as well as fires involving ordinary combustibles, could occur in a typical fuel transfer area.

No single agent is completely effective in extinguishing and securing all of these types of fires, especially when the area is subject to moderate-to-high ventilation. Under this worst-case condition, a combination of suppressants is required for total protection.

The most effective combination of agents is AFFF and multipurpose dry chemical. The dry chemical achieves quick "knockdown" of the initial flame. The AFFF forms a fast-spreading film over the spilled fuel, preventing the escape

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

of flammable vapors and thereby eliminating the possibility of reignition. This type of "twin-agent" system, utilizing AFFF and multipurpose dry chemical, is commonly used at airports, petrochemical plants, and in other high-hazard facilities where flammable and combustible liquids are present.

Controls

System control options include manual operation, automatic operation, and automatic operation with manual override. A manually operated system could use hand portable extinguishers, hose reels, and/or an overhead network of fixed piping and nozzles for suppressant distribution; whereas automatic and automatic-with-manual-override systems would use only fixed piping and nozzles. However, installation of a fixed suppression system does not eliminate the need to provide hand portable extinguishers in the area.

The most important criterion in selecting a system control is extinguishing response time. Rapid extinguishment is critical for several reasons:

1. The longer the preburn time (elapsed time between ignition and attempted extinguishment), the more difficult extinguishment becomes. Fuels are heated to temperatures above their flashpoints, and involved surfaces become potential sources for reignition (after fire-suppressant discharge). Secondary combustibles, such as wood or rags may be ignited and the fire may grow in size and area beyond the limits of suppression system coverage.
2. The fire may block safe egress of personnel, or personnel may be injured and threatened by the fire directly.
3. Finally, as long as the fire is permitted to burn, copious amounts of toxic combustion products, such as carbon monoxide, are generated.

Manually operated suppression systems depend on the prompt and appropriate response of attending personnel. If personnel are not present, or if they panic or are injured, activation of the suppression system may be delayed to the point where extinguishment cannot be assured. Worse, the system may not be activated at all.

Automatic system operation offers a higher level of protection than manual operation. Automatic control with the added security of a manual override capability is the recommended option. Although the potential for false alarms exists with automatic operation, the seriousness of an uncontrolled fueling area fire justifies this remote risk.

Detection

Automatic system operation requires the use of a detection system to trigger discharge of the suppressant. Detection options considered included heat, smoke, and flame.

Heat, or thermal, detectors, which depend on convected thermal energy for alarm activation, have a proven history of high reliability and low maintenance requirements, even when used in harsh environments. However, the response of thermal sensors may be unacceptably slow, especially in areas subject to moderate-to-high ventilation.

Smoke detector responses are typically much faster, but as with thermal detectors, response is affected by local air currents. In addition, nuisance alarms can be expected to result from dust accumulations, humidity changes, and exposure to blasting fumes and diesel exhaust.

Flame detectors offer the fastest response possible. They are designed to respond to the infrared, visible, and/or ultraviolet light emitted by a fire. Ultraviolet and infrared detectors are routinely used in rugged industrial settings such as offshore oil platforms, petrochemical plants, and aircraft hangars. Maintenance is generally confined to cleaning the optical lenses. Typical sources of nuisance alarms include lighting and arc welding for ultraviolet detectors and hot surfaces or gases for infrared detectors.

Ultraviolet detection is recommended for fuel transfer area fire protection systems. Thermal detection was ruled out because it is inherently slower than the other methods. In moderately to highly ventilated areas, detection delays would permit excessive preburn times. Smoke detection was ruled out because frequent nuisance alarms would result from constant vehicular traffic. Infrared detectors were rejected because false alarms could be triggered by hot engine surfaces and exhaust gases. Ultraviolet detection therefore provides the fastest and most reliable fire signal. Although arc welding within the optical field of view of an ultraviolet detector could cause a false alarm, such an occurrence could be avoided by disabling the detection system while the welding operation is performed.

Figure 2 illustrates the recommended design concept for the fuel transfer area fire sensing and suppression system. This concept features twin-agent suppression, ultraviolet flame detection, and automatic-with-manual-override control.

Fuel Storage Area

The storage area fire protection system also consists of suppression, control, and detection subsystems.

Suppression

As discussed previously, AFFF, high-expansion foam, and Halon 1301 are all effective in extinguishing and securing a typical combustible-liquid spill fire in unventilated areas such as a completely enclosed fuel storage area. Although dry chemical is not capable of securing combustible liquids against reignition, its overall suppressant rating is higher than those of AFFF and high-expansion foam because of its greater extinguishing effectiveness on combustible-liquid pressure and running-fuel fires. All four agents are considered acceptable for this application; however, for optimum protection, an AFFF and dry chemical twin-agent system is required.

Controls

The same system control options as were discussed for the fuel transfer area—manual, automatic, and automatic with manual override—exist for the storage area. The same selection criteria apply as well. Again, the overall level of safety is higher with automatic operation than with manual operation, and the optimum system would provide the added security of a manual override discharge capability. Such an optimum system will minimize preburn time, heating of involved surfaces, ignition of secondary combustibles, fire spread, and the generation of toxic products of combustion.

Detection

Because the fuel storage area is completely enclosed, fewer constraints are imposed on detector selection. Although thermal detection is inherently slower than smoke or flame detection, acceptable response times could be achieved with a properly designed thermal detection system in this area. Smoke detection would also be acceptable, however, optimum system performance requires flame detection. Either infrared or ultraviolet detection could be used.

Figures 3 through 7 show recommended fuel storage area fire sensing and suppression system layouts utilizing AFFF, high-expansion foam, Halon 1301, dry chemical, and twin-agent suppressant, respectively. Each system depicted in-

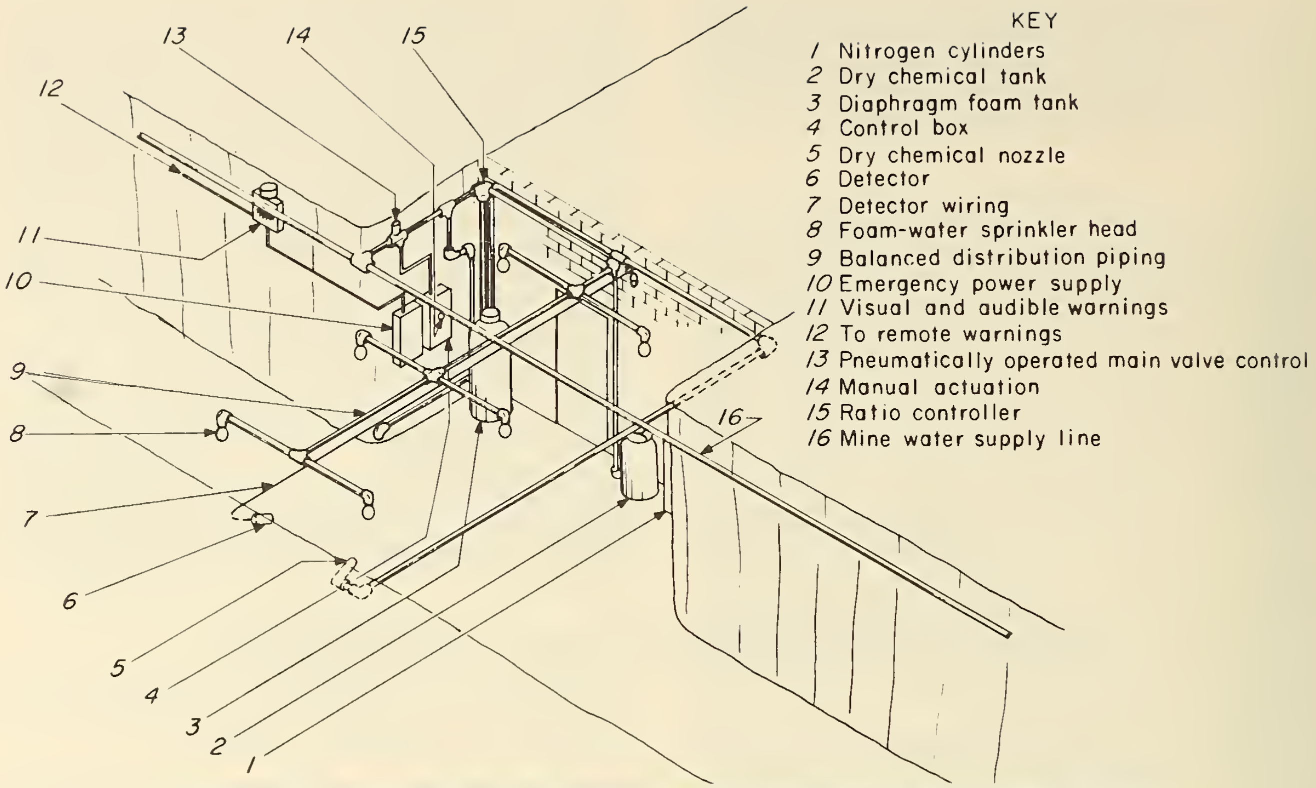

FIGURE 2.—Recommended fuel transfer area fire sensing and suppression system.

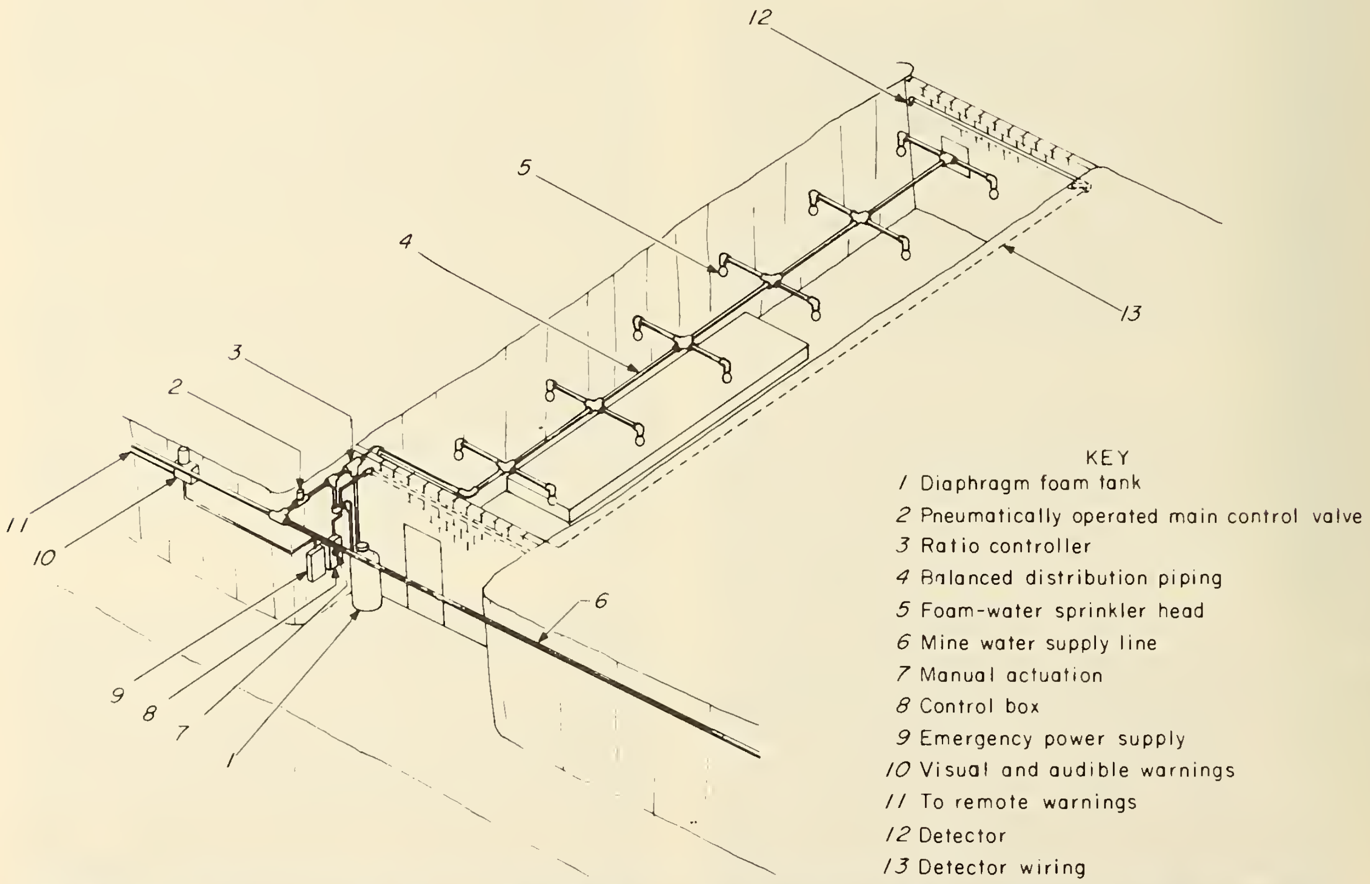

FIGURE 3.—Recommended fuel storage area fire sensing and suppression system utilizing AFFF suppressant.

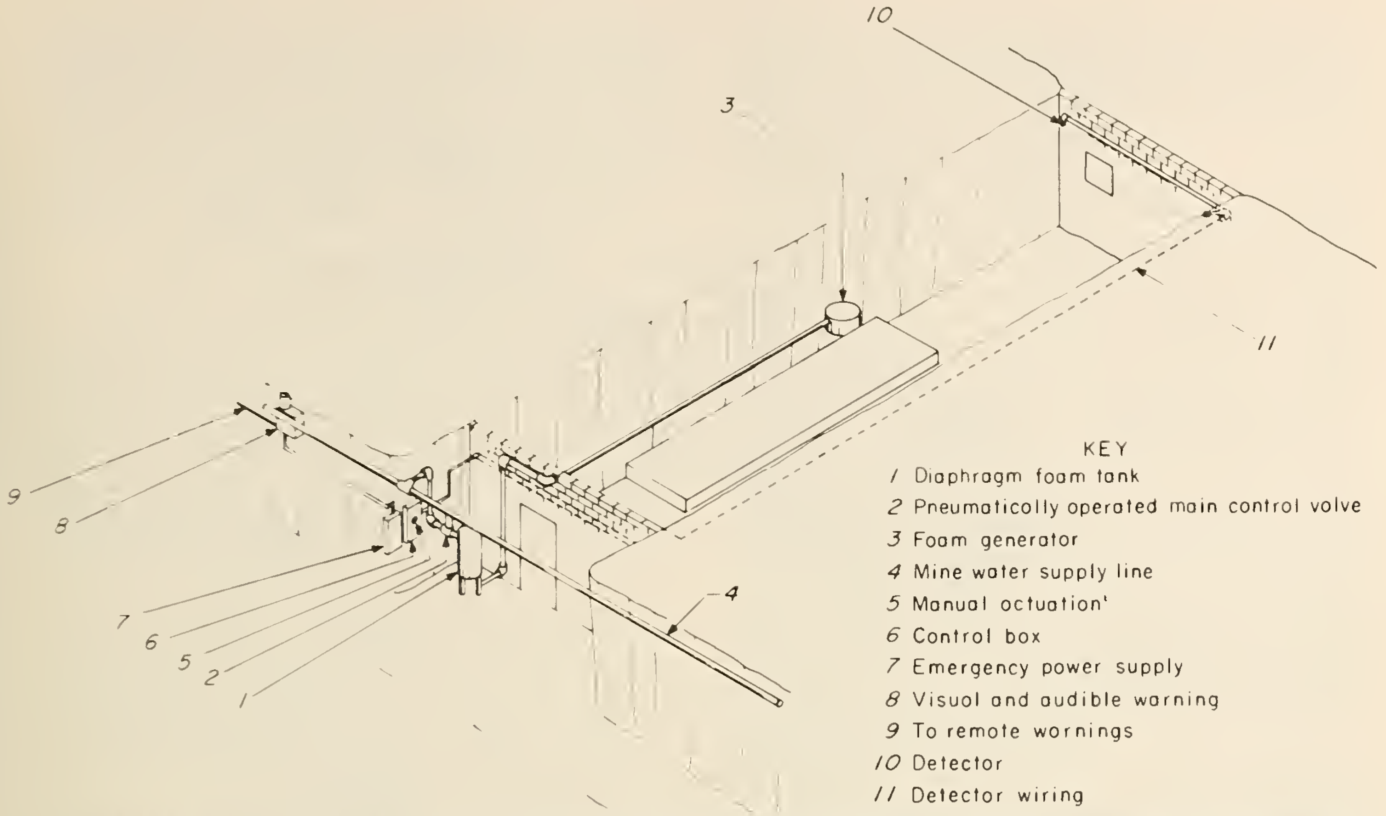

FIGURE 4.—Recommended fuel storage area fire sensing and suppression system utilizing high-expansion foam suppressant.

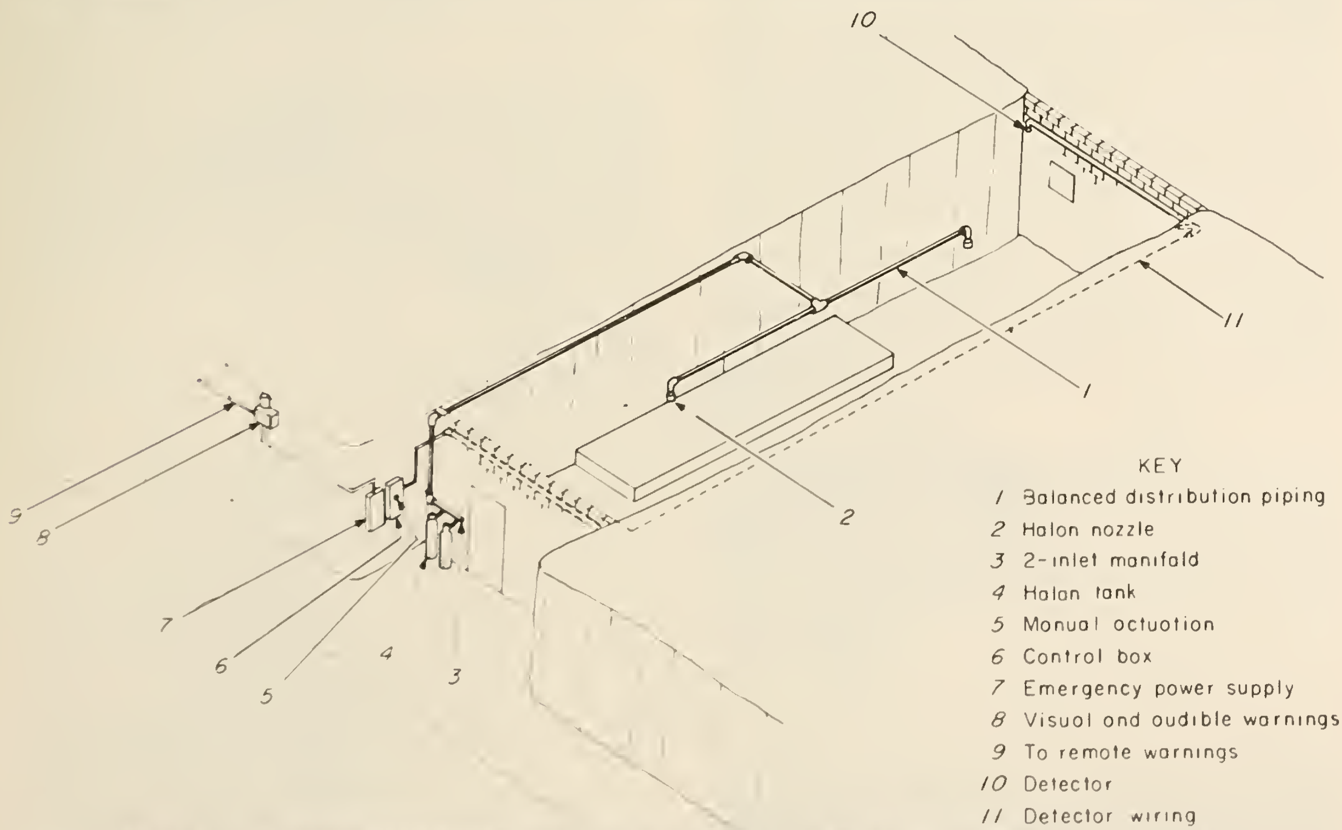

FIGURE 5.—Recommended fuel storage area fire sensing and suppression system utilizing Halon 1301 suppressant.

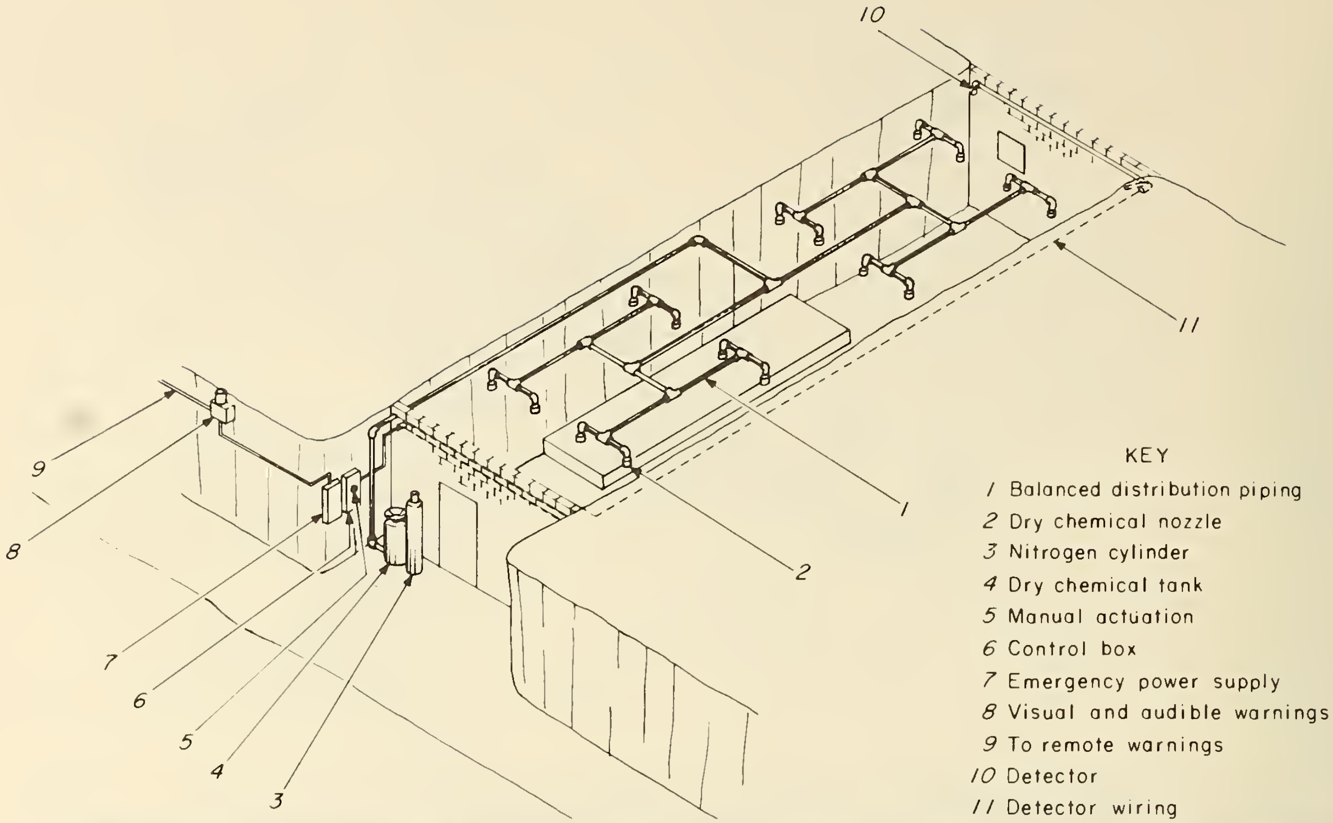

FIGURE 6.—Recommended fuel storage area fire sensing and suppression system utilizing dry chemical suppressant.

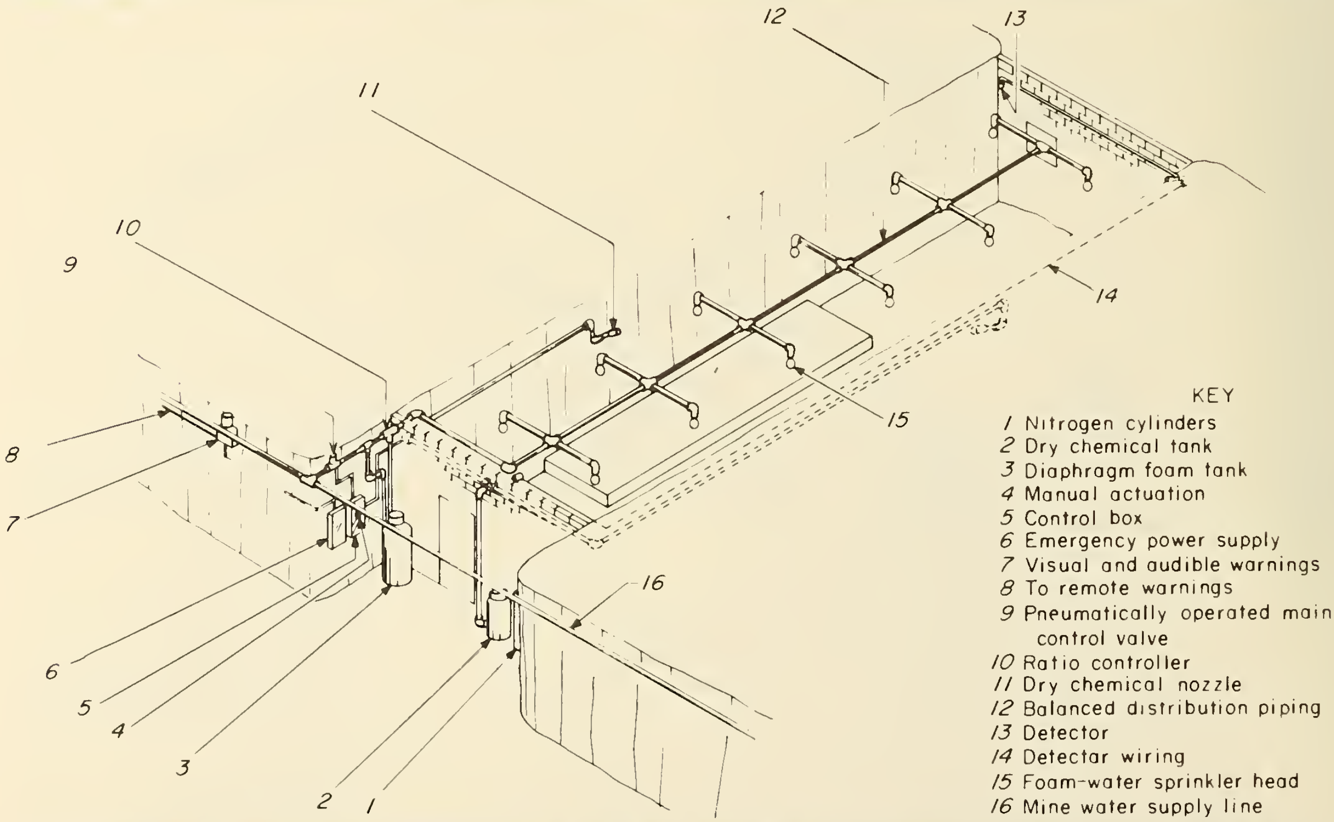

FIGURE 7.—Recommended fuel storage area fire sensing and suppression system utilizing twin-agent suppressant.

cludes ultraviolet flame detection; however, as noted above, thermal, smoke, or infrared flame detection would also be acceptable. For AFFF, dry chemical, and twin-agent suppression, direct application of suppressant is most effective. Thus, numerous nozzles are distributed throughout the hazard area. However, Halon 1301 and high-expansion foam quickly expand to fill the available enclosure space, making fewer discharge points necessary.

Additional Design Considerations

The foregoing analysis specifies the basic elements that should be included in fire protection systems for underground fuel transfer and storage areas. Additional design considerations relating to reliability, maintenance and system complexity are discussed below. In a survey of 18 mine managers, reliability, maintenance, and costs were identified as the three most important criteria for equipment selection. In later sections of the report, comparative cost data are presented and cost-effectiveness analysis of fire protection systems is discussed.

System Reliability and Maintenance

Where the proper function of a system depends on the proper function of all of its components, overall system reliability is expressed as follows:

$$R_s(t) = (R_{c1}(t)) \times (R_{c2}(t)) \times (R_{c3}(t)) \ldots (R_{cn}(t))$$

where $R_s(t)$ = system reliability over time interval t

and $R_c(t)$ = component reliability over time interval t.

Thus, system reliability is maximized when the reliability of individual components is maximized and when the number of individual components is minimized.

Reliability of Individual Components

Individual component reliability generally follows the pattern shown in the idealized failure rate curve (fig. 8). The initial period is characterized by a relatively high failure rate due to manufacturing and installation defects or applications that exceed the recommended duty cycle or environmental restrictions of the component. It is sometimes referred to as infant mortality. The middle period is characterized by a low failure rate. Failures during this period are the result of random events. It is sometimes referred to as the useful life or prime of life. The final period is characterized by a high and asymptotically increasing failure rate, which results from components wearing out. This period is sometimes referred to as the wearout or burnout phase.

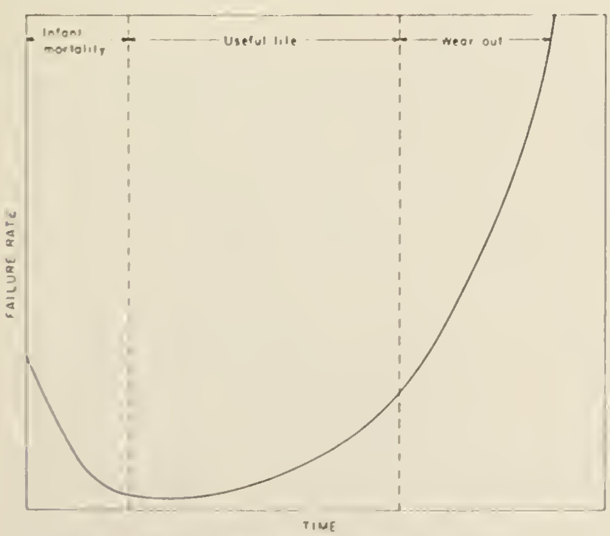

FIGURE 8.—Idealized failure rate curve.

Careful selection of components, with particular attention to manufacturing quality control, rated duty cycles, and environmental restrictions can help minimize infant mortality. The performance of similar components operated under similar conditions can also guide equipment selection. In addition, components that are listed or approved by one of the various nationally recognized independent testing laboratories can be specified. Components are listed or approved by these laboratories only after they have been thoroughly tested and found to meet or exceed the requirements of rigorous environmental and operational standards.

Periodic inspection is necessary to detect random failures that may occur during the component's useful life. How often inspections are necessary is determined through long-term observation of the system in operation. The fire sensing and suppression systems described above require weekly visual checks. Typical inspection items include inspecting nozzles for obstructions, checking pressure gauges for pressurized components, noting general appearance of components for mechanical damage and corrosion, and checking the position of main water-supply valves.

If component failure is to be avoided, preventive maintenance (PM) is necessary to ensure that components will be repaired or replaced as necessary before they wear out. Manufacturer-recommended PM programs are designed to extend the useful life of a component and/or preempt component failure by replacement before wearout failures occur. Various components of the fire sensing and suppression systems require PM at 6-month, 1-yr, 2-yr, and 5-yr intervals.

Typical maintenance items include testing suppression system actuation mechanisms for proper function and pneumatic actuation lines for leaks (no agent discharge required); weighing pressurized components and comparing to fill levels indicated by pressure gauges; testing detectors with test flames; testing all visual and audible alarms and other system control features; checking fill levels of nonpressurized suppressant-agent containers; and hydrostatic testing of pressure vessels. Component repair or replacement should be performed when necessary. In addition, conditions causing undue wear to components should be corrected if possible.

System Complexity

The fire sensing and suppression systems discussed are as simple and straightforward as could be designed and yet still perform as required. As few individual components as possible were included in each design. Each system consists of predesigned and manufactured modules to simplify assembly, installation, inspection, maintenance, and operation.

COSTS

Costs of detection, suppression, and control equipment would vary according to the nature of the hazards that might be expected and the size of the area covered by the system. Table 4 contains estimated costs for five alternate fire protection systems for a typical enclosed fuel storage area 65

TABLE 4.—System cost comparisons

(Fire sensing and suppression systems for fuel storage and fuel transfer areas using various suppressants; estimated costs in 1983 dollars)

	Suppressant				
	AFFF	High-expansion foam	Halon 1301	Dry chemical	Twin agent
Equipment	$10,600	$10,900	$10,300	$10,300	$16,500
Installation	4,400	3,000	3,000	5,200	6,100
Operation	1,500	1,200	2,600	370	3,000
Maintenance, annual	300	300	370	370	500
Total	16,800	15,400	16,270	17,370	26,100

AFFF Aqueous film-forming foam.

ft long, 20 ft wide, and 13 ft high, containing 1,250 gal of combustible liquids. A fuel storage area was chosen for this example over a fuel transfer area because only one system type (twin agent) was recommended for the transfer area, whereas all five types (twin agent, high-expansion foam, Halon 1301, dry chemical, and AFFF) were judged acceptable for the storage area. Included in each estimate, as a part of equipment cost, is $4,400 for detection (ultraviolet flame) and control (automatic with manual override).

The installation cost estimates in table 4 are for installations by a fire protection contractor. Significant savings could be realized if mine personnel installed the system.

Overall system cost-effectiveness is discussed in a later section of this report.

ALTERNATIVE SYSTEM DESIGNS

Like the guidelines for fueling system design, the recommended conceptual designs for fuel transfer area and fuel storage area fire protection systems represent optimum rather than minimum approaches. Also, these concepts are based on certain assumptions regarding the layout of the fueling area, such as fuel transfer area ventilation, storage area enclosure, etc. Alternative system elements may result in a higher level of safety depending on local conditions. However, the rationales presented in this report for selecting system elements can provide useful guidance if alternatives are considered.

PROTOTYPE FIRE SENSING AND SUPPRESSION SYSTEM

A complete fire sensing and suppression system was designed, fabricated, and tested under laboratory conditions and in an underground mine to evaluate the feasibility, practicality, and overall effectiveness of the system under simulated and actual mining conditions.

GENERAL DESCRIPTION

The prototype fire sensing and suppression system (fig. 9) was designed in accordance with the generic design concepts discussed previously. Each system element is discussed in detail below.

Suppression

Since the site selected for in-mine tests was not enclosed and combined both storage and transfer of fuel, a twin-agent AFFF and multipurpose dry chemical suppression system was specified.

AFFF Subsystem

The AFFF subsystem contains a main control valve, a water pressure and flow control unit, a concentrate bladder tank, a water-concentrate proportioner, and a distribution system of pipe and nozzles.

The pneumatic pressure from the control unit operates the main control valve of the AFFF subsystem, initiating water flow from the mine water supply line. The flow and pressure of this line are maintained at constant levels through the use of a pressure-reducing valve. This flow of water is used to fill the volume of the bladder tank between the bladder and the tank wall, pressurizing the concentrate inside the bladder. The concentrate is then forced out of the tank and into the proportioner, where it is mixed with the main water flow to yield a solution containing concentrate. The solution then flows through the piping to the nozzles, where air is drawn into it to form the foam that is discharged onto the hazard.

Eight standard nozzles, each providing 100 sq ft of coverage, are required to cover the fueling area. At the required minimum delivery rate of 0.1 gpm/sq ft of protected area, the 800-sq-ft fuel storage area would require 80 gpm of foam discharge. A minimal 10-min discharge would require a 24-gal AFFF concentrate tank. Increasing the pressure of the foam-water sprinkler nozzle to 30 psi to provide a higher quality foam would yield 16 gpm per nozzle or 0.16 gpm/sq ft of area. The 800-sq-ft area would then require a 128-gpm discharge and a 40-gal AFFF concentrate tank for a 10-min discharge. Utilizing a 70-gal concentrate tank and operating eight nozzles at 16 gpm per nozzle, the actual foam flow time would be 18.2 min. The distribution piping was hydraulically calculated and sized to provide nearly equal nozzle pressures to all eight nozzles.

The AFFF agent used in this system is a 3-pct-type concentrate intended for use by dilution or proportioning at a 3:97 volume ratio with water. At present, there are no Federal or military specifications covering this type of concentrate. Specification MIL-F-24385A, 2 May, 1977 (U.S. Navy), covers 6-pct AFFF concentrates and requires performance at 3-pct, 6-pct, and 50-pct concentrations before and after aging for 10 days at 150° F of both the concentrate and premixed fresh and salt water solutions.

The concentrate used in this system meets all of the fire-performance requirements specification of MIL-F-24385A. It also has been tested and found to perform equally well in water having a hardness (calcium and magnesium) of 500 ppm. The AFFF concentrate is a mixture of fluorochemical surfactants, hydrocarbon surfactants, and solvents. It is specifically formulated to have low corrosion characteristics on most common metals and a low environmental impact.

The nozzles are aspirating-type, upright foam-water sprinkler nozzles with 1/2-in NPT connections and a 3/8-in throat. They provide good-quality foam during discharge.

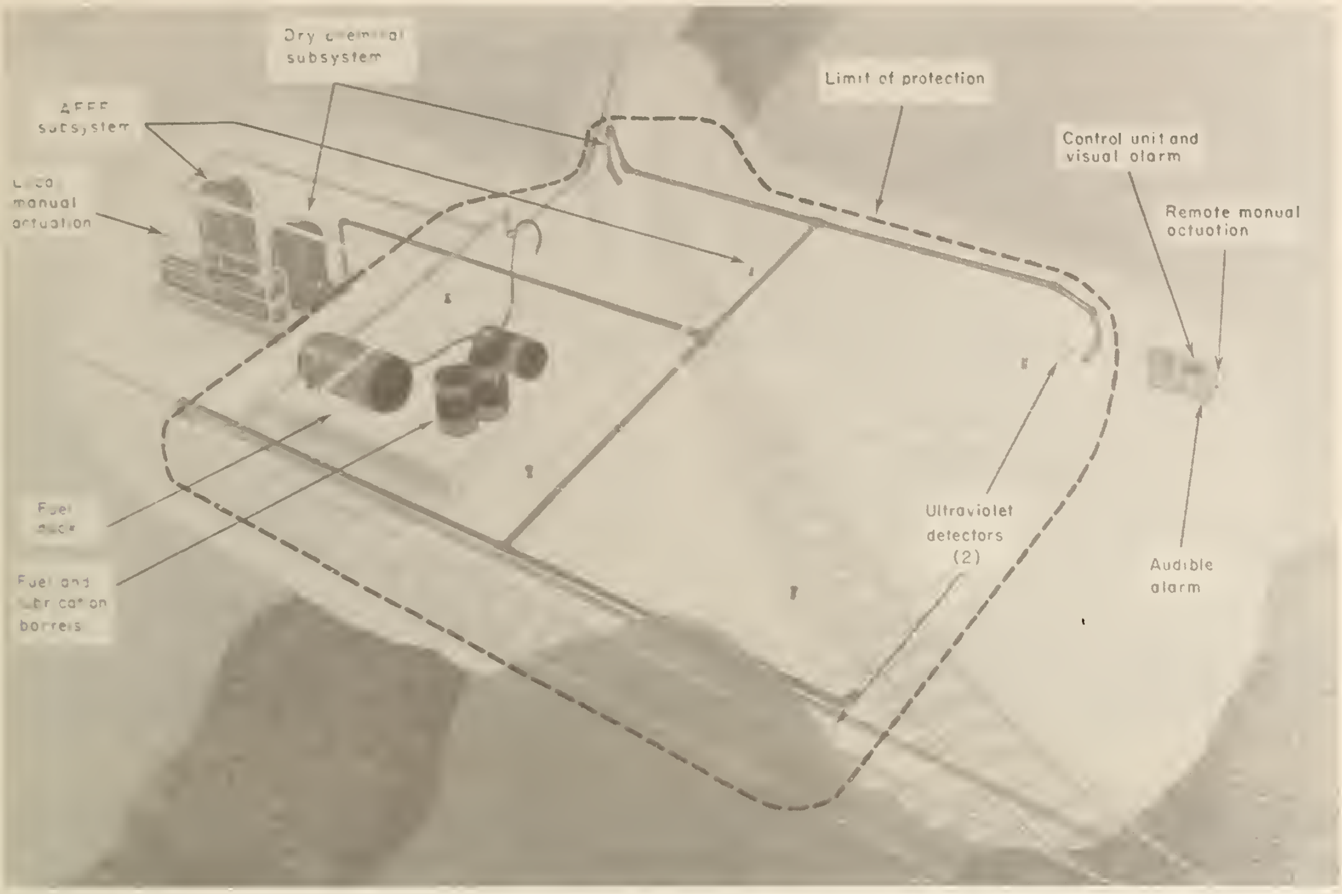

FIGURE 9.—Prototype fire sensing and suppression system for underground fuel storage and transfer area.

The AFFF system is designed for an operating temperature range of 32° to 120° F. This system should not be used where temperature may drop below 32° F because the AFFF solution will freeze.

Corrosion protection is accomplished with bronze valves and fittings and brass piping, and the entire unit has a special epoxy coating.

Dry Chemical Subsystem

The dry chemical subsystem consists of three major components: the nitrogen power supply, the dry chemical storage container, and the distribution system composed of piping and nozzles. Pneumatic pressure from the control-unit cartridge opens all nitrogen cylinders simultaneously, releasing the nitrogen through pressure regulators to pressurize the storage container and fluidize the dry chemical. When the storage container reaches a predetermined pressure, a frangible disc in the outlet piping bursts, releasing the dry chemical into the piping. Pre-aimed stationary nozzles discharge the dry chemical onto the hazard.

The dry chemical tank provides for the storage of 425 lb of agent. The agent is suitable for use on fires involving cellulosic-type fuels such as wood, paper, plastics, etc., as well as flammable and combustible gases and liquids. Federal Specification 0-D-1380A, July 12, 1968 (General Services Administration), details the composition and physiochemical properties of the type of agent used. The agent is a finely divided solid cnsisting of about 90 wt pct monoammonium phosphate. The remaining 10 pct consists of materials to improve flow and packing characteristics and reduce hygroscopicity such as clays, colloidals, silicas, and polymeric siloxzines. This agent is compatible with AFFF in a separate or simultaneous application.

The four 1-1/2-in dry chemical nozzles provide a fan-shaped pattern for a large-area sweep and will distribute the dry chemical at a flow rate of about 12 lb/s. The distribution piping for the dry chemical subsystem is schedule 40 hot-dipped galvanized pipe. A balanced piping arrangement is used to distribute the dry chemical evenly to each of the four nozzles.

The dry chemical subsystem is designed for and can be operated in the temperature range of −40° to 120° F.

All components have a heavy external epoxy coating for protection against highly humid or corrosive atmospheres. The system is completely sealed to prevent internal corrosion.

Detection and Control

The detection and control subsystem contains ultraviolet detectors monitored by a control panel that provides a pneumatic output to the suppression subsystem when flames are present within the cone of vision of the detectors.

The detectors are self-contained 24-V dc units that provide both instantaneous and time-delayed contacts as outputs. The control system utilizes 5-s-delay contacts as a zone-alarm input, leaving the instantaneous contacts available for additional remote annunciation on an individual-detector basis if required. The detectors are equipped with an "optical integrity" feature that allows remote testing of the condition of their

optical lenses. The detectors are housed in an explosion-proof enclosure and are easily installed with integral swivel mounts and brackets.

Two detectors are required for this system. They are positioned in the fueling area so their 90° fields of vision overlap, with each detector covering the entire area. The two detectors are cross-zoned within the control unit—meaning that both detectors must sense the fire before the fire signal passes to the actuation device—to minimize false alarms.

The fire signal operates a mechanical device that releases an internally stored pressurized gas to operate the suppression subsystem. The control unit has an internal adjustable time delay to delay actuation of the suppression system until a predetermined time has elapsed after the alarm input is received. It also has an abort function to permit system maintenance without nuisance alarms.

TESTS

Laboratory Component Testing

All system components were analyzed for their suitability for use in a harsh underground mine environment. For components with insufficient histories of performance in underground environments, tests were performed in the laboratory under simulated mining conditions.

Suppression

AFFF subsystem components were selected with corrosion resistance as the major consideration. Components not normally used in AFFF systems, such as the main control valve and pressure-reducing valve, were chosen based on materials of construction and simplicity of operation. Since little data was available on the performance of the main control valve and pressure-reducing valve under the conditions anticipated in the mine, specialized performance tests were devised and conducted for these components.

Operational testing on the pneumatically operated main control valve consisted of obtaining the torque output from the actuator before and after prolonged corrosion testing in a salt spray. The result of the salt spray was a decrease in torque output significant enough to cause concern. Therefore, a new actuator was obtained and modified to prevent corrosive atmospheres from affecting the internal parts of the actuator. Gaskets and plugs were used to seal joints, and 0-rings were added to the actuator shaft to eliminate seepage between the shaft and body. A second salt-spray test on the redesigned actuator gave satisfactory results.

The objective of the pressure-reducing valve tests was to determine pressure setting versus flow and pressure. No operational problems were encountered during any of the tests. The pressure-reducing valve provided leak-free operation and consistently reduced pressures downstream.

Due to previous testing and past performance in actual use, the dry chemical subsystem was considered to be rugged and corrosion resistant enough to withstand the atmosphere and hard usage it would encounter underground. Components of the system such as cylinders, valves, hoses, gauges, and other equipment have all undergone salt-spray, shock, vibration, and operational tests to obtain listings by Underwriters Laboratories, Inc., and Coast Guard marine approval. Dry chemical installations on offshore platforms are exposed to severely corrosive environments, yet they function for extended periods without failure.

Detection and Control

All of the component parts of the detection and control subsystem have been extensively tested and are listed by Underwriters Laboratories. The ratings and limitations of the detection system and the capabilities of the emergency power supply and control equipment are predefined by Underwriters Laboratories.

Laboratory Full-Scale Fire Testing of Complete System

As a last step prior to in-mine installation and testing, the complete prototype system was subjected to full-scale fire tests in a specially designed fire-test fixture.

The fire hazard consisted of a 50-sq-ft pan fueled with 2 in of heptane. Heptane was used instead of diesel fuel for ease of ignition and also because it has a much hotter flame and is more difficult to extinguish. A vehicle mockup was situated directly over the pan to simulate a fire under a vehicle during the refueling operation and to provide an obstacle to fire-suppressant agent coverage.

The AFFF subsystem was installed with four nozzles spaced 10 ft apart in a grid and suspended 10 ft directly over the hazard. The dry chemical unit was installed with two of the four nozzles aimed at the hazard. System actuation was provided by pneumatic actuation lines running from the AFFF and dry chemical subsystems to the control unit. The configuration of system elements for mockup testing is shown in figure 10.

The heptane was ignited and allowed approximately a 15-s preburn, which gave total fuel involvement. At 15 s, one detector was aimed at the fire; it instantaneously actuated the control unit. Flow from the AFFF subsystem began immediately—pure water for the first 5 s and, once stabilized, foam thereafter. The cooling effect of the foam decreased flame intensity slightly.

When the AFFF control valve was opened, the nitrogen cylinder valves on the dry chemical unit simultaneously opened, beginning pressurization of the dry chemical tank. A 12-s delay was built into the dry chemical unit by use of the frangible disc, allowing pressure to build in the tank and fluidize the dry chemical

The time span between the bursting of the disc and complete extinguishment (fig. 11) was approximately 3 s. The total time from detection to extinguishment, during which foam flow had already begun, was approximately 15 s.

Additional tests were conducted to determine the effectiveness of AFFF and dry chemical used separately on spill fires obstructed from the overhead nozzles by the vehicle mockup. Neither AFFF nor dry chemical alone was able to extinguish such a fire.

Field Test

The site selected for field tests was a fuel dock in Union Carbide Corp.'s Pine Creek tungsten mine near Bishop, CA. A description of this site is provided in table 5. The complete sensing and suppression system was disassembled, shipped to the mine site, installed, debugged, and fire tested in the mine.

Installation, Inspection, and Pretests

Underground installation took 5 days and proceeded as planned with no major difficulties. The installation of the detection and control subsystem (figs. 12–13) was completed first, and detector performance was monitored for several

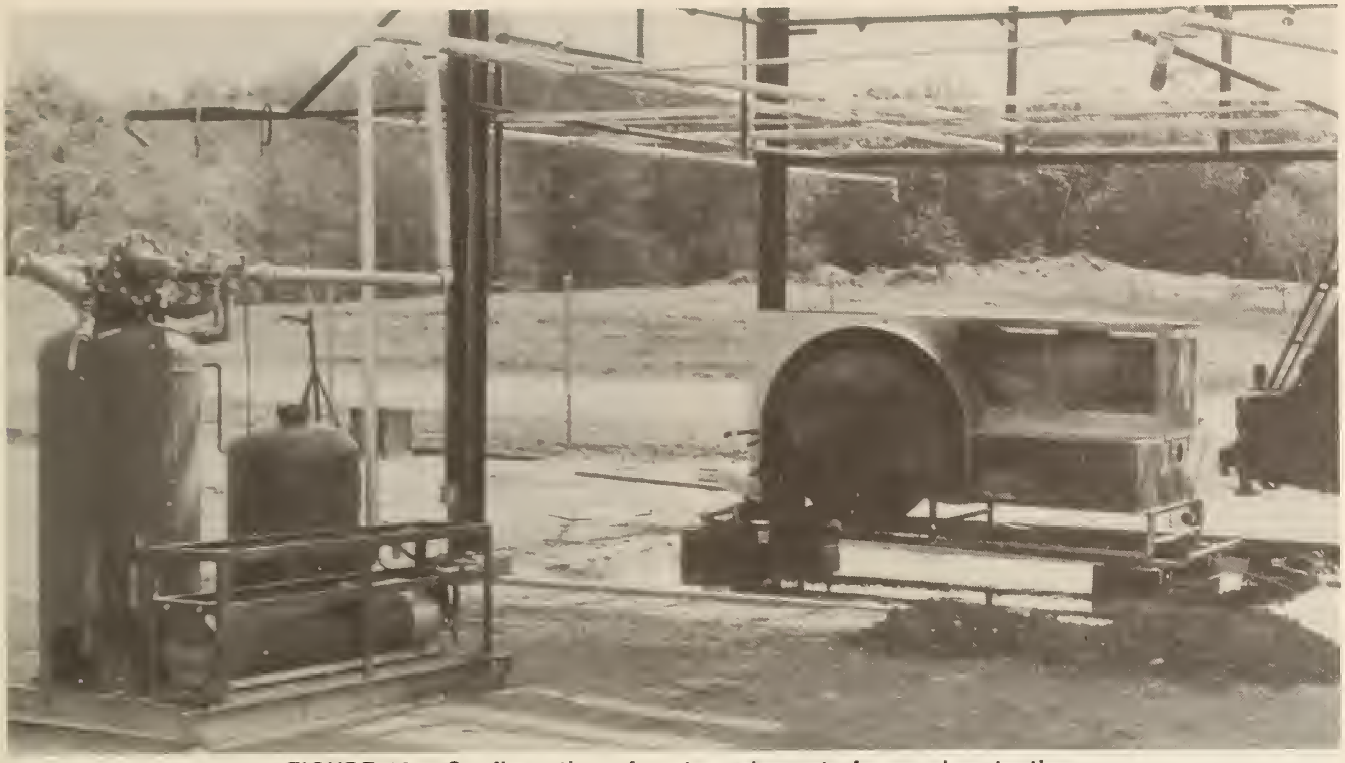

FIGURE 10.—Configuration of system elements for mockup testing.

FIGURE 11.—Twin-agent discharge during mockup testing.

days prior to the fire tests. Temporary equipment installed included a switch to prevent premature firing of the system while the test fires were being ignited.

During 3 days of monitoring, no false alarms or other problems occurred. On the fourth day, a malfunction was discovered in an unused portion of the time-delay circuit. The cause was determined to be the temperature-humidity effect of the underground atmosphere. A simple bypass of the cir-

TABLE 5.—Test site description

(Fuel dock in Pine Creek tungsten mine)

Parameter	Quantity
Environment:	
Ventilation . . . fpm	90
Temperature . . . °F	40–45
Humidity . . . pct	90–100
Dimensions:	
Area . . . sq ft	750–800
Height . . . ft	10
Flammables, gal:	
Diesel fuel	135
Motor oil	110
Hydraulic oil	110
Class A	None
Water supply:	
Static pressure of 4-in main supply (nominal) . . . psi	200
Total hardness . . . mg/L	28.0
pH	7.1
Electrical supply (for 3 200-W explosion-proof lamps):	
Voltage . . . V	110
Current . . . A	20

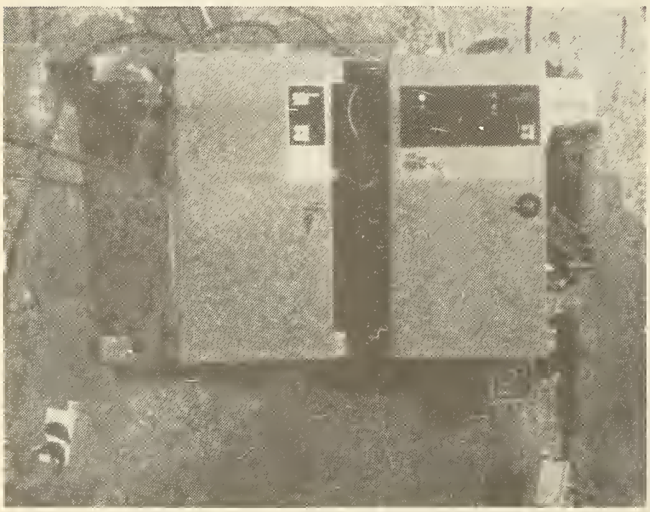

FIGURE 12.—System control panel.

FIGURE 13.—Ultraviolet flame detector head.

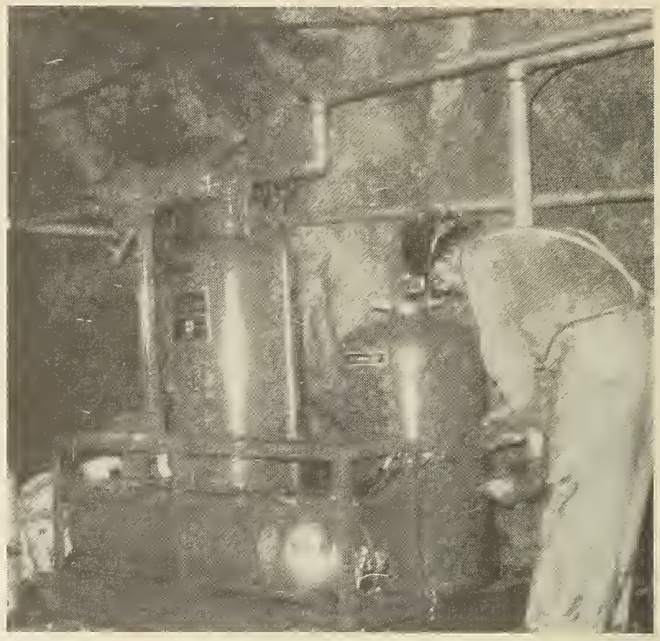

FIGURE 14.—Twin-agent suppression subsystem (exclusive of distribution network).

cuit solved the problem; however, a new circuit board that included a permanent solution to this problem was later installed.

The AFFF-dry chemical suppression module (fig. 14) was positioned adjacent to the fuel dock. Dry chemical and foam piping networks (figs. 15–16) were cabled to roof bolts and/or J-bolts.

Following installation, the system was checked out by means of scheduled pretests. Prior to the fire tests, the system was given a complete maintenance inspection and discharge test. The detectors were checked from the test panel and also by using a cigarette lighter flame. All cartridge actuators were operated to assure leak-free tubing and normal actuation. A 50-lb discharge of the multipurpose dry chemical was initiated to assure proper fluidization of the dry chemical, proper frangible-disc rupture, and proper nozzle location and aim.

During the last actuation sequence, pressure gauges were installed at the water inlet and at one nozzle. Static inlet pressure was 210 psi from the 4-in mine water supply line. Flow pressure at the inlet was 55 psi, but the distribution-

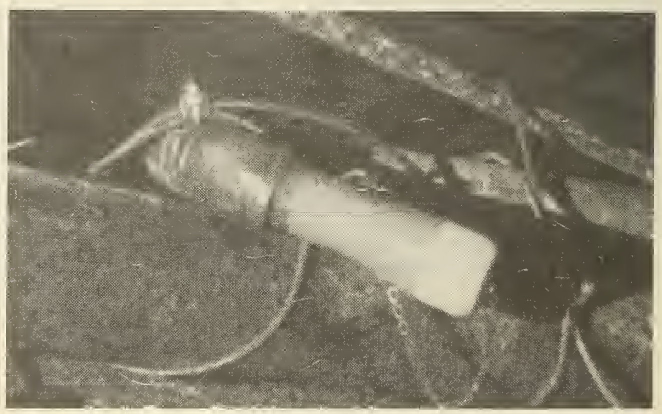

FIGURE 15.—Dry chemical nozzle with blowoff cap.

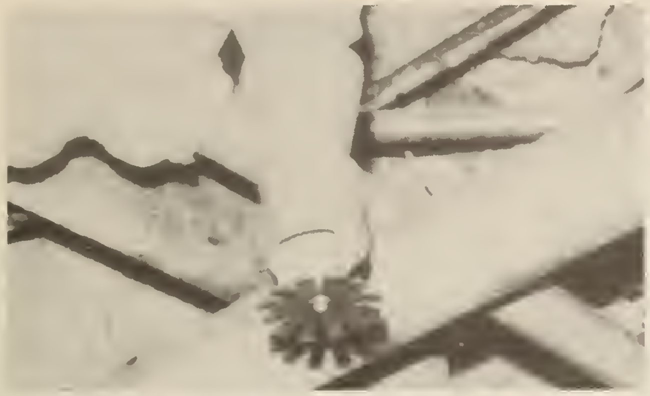

FIGURE 16.—Foam-water sprinkler nozzle.

piping head loss lowered the nozzle flow pressure to 12 psi. The pressure-reducing valve setting was increased in an attempt to obtain the desired nozzle pressure of 30 psi. However, 12 psi was the maximum nozzle pressure attained during stabilized flow. At 12 psi, the nozzle pressure-flow curve indicates a flow rate of 10.5 gpm. This flow rate is barely enough to maintain the minimum required foam flow of 0.1 gpm/sq ft.

Fire Testing

Since Federal mine safety regulations (30 CFR 57.4–58) prohibit the lighting of fires underground, it was necessary to obtain a variance in order to perform the field testing. Both the Mining Enforcement and Safety Administration (now MSHA) and the California Department of Industrial Relations granted the necessary variances. The field testing was performed in accordance with these variances.

Using a temporary switch added to the control panel, the automatic suppression system discharge circuit was rendered inoperable. Fires could thus be permitted to grow to full involvement before suppressant discharge. (If operated in the automatic mode, the detectors would have sensed the fire instantly, and suppression would have begun before full involvement of the fuel.)

The first underground fire test was the extinguishment of a 2- by 3-ft pan fire placed (unobstructed) on the fuel storage pad. The pan contained approximately 2 gal of water supporting 1 gal of diesel fuel. For this test, the dry chemical subsystem was disconnected and only the foam system was actuated. After ignition and a 15-s preburn time, the AFFF system was manually actuated. The fire was completely extinguished in 10 s.

The second fire test was conducted utilizing the same pan and the same amounts of water and fuel. The pan was placed under the vehicle mockup to simulate an obstructed spill under a vehicle (fig. 17). The fuel was ignited (fig. 18) and was fully involved 10 s after ignition (fig. 19). The AFFF system was manually actuated, and the dry chemical system frangible disc ruptured 13 s later (fig. 20). Complete extinguishment was achieved 3 s after actuation of the dry chemical system (fig. 21).

Carbon monoxide sampling was performed following each test, however, measurable quantities could not be detected. After 43 months of reliability testing in the mine with the system operating in the automatic mode, no problems have been encountered.

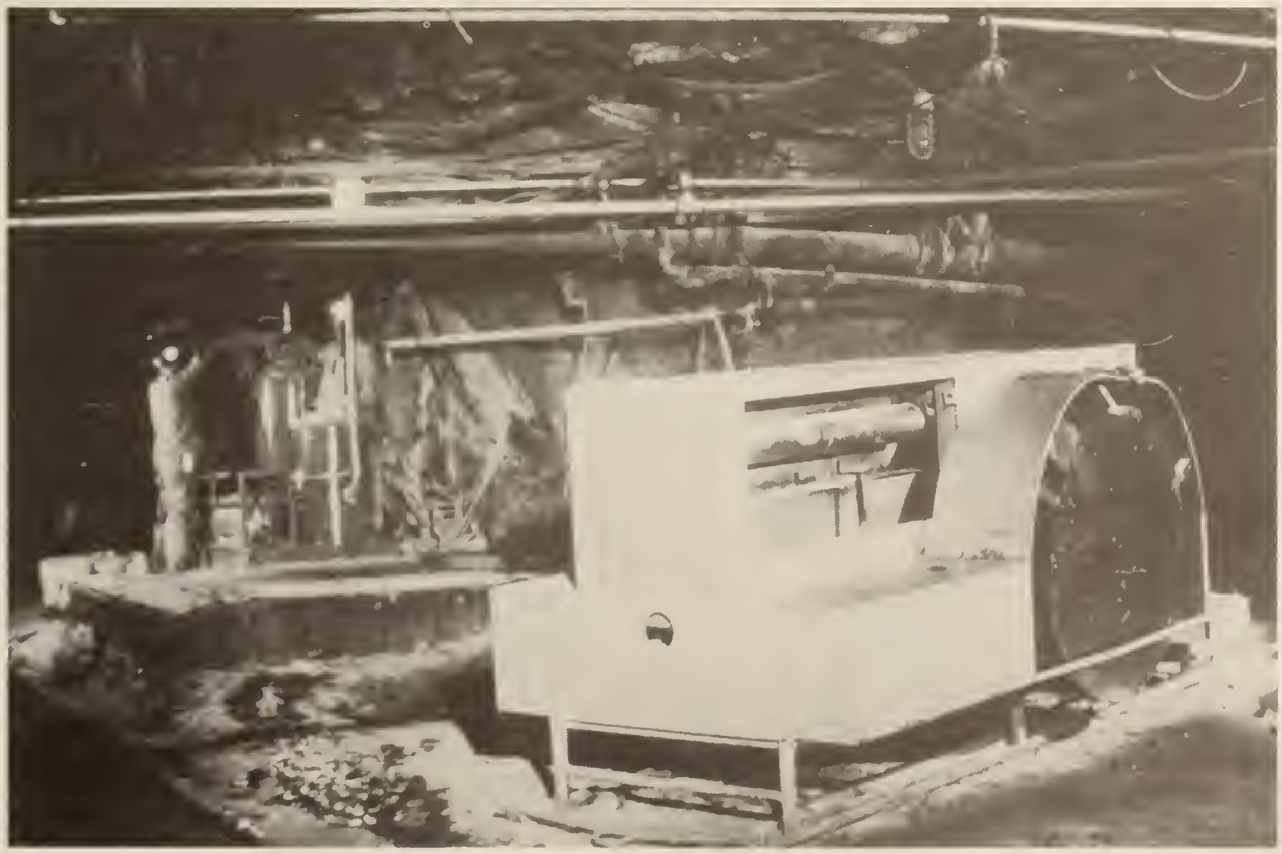

FIGURE 17.—Vehicle mockup in fuel transfer area.

FIGURE 18.—Igniting test fire beneath vehicle mockup.

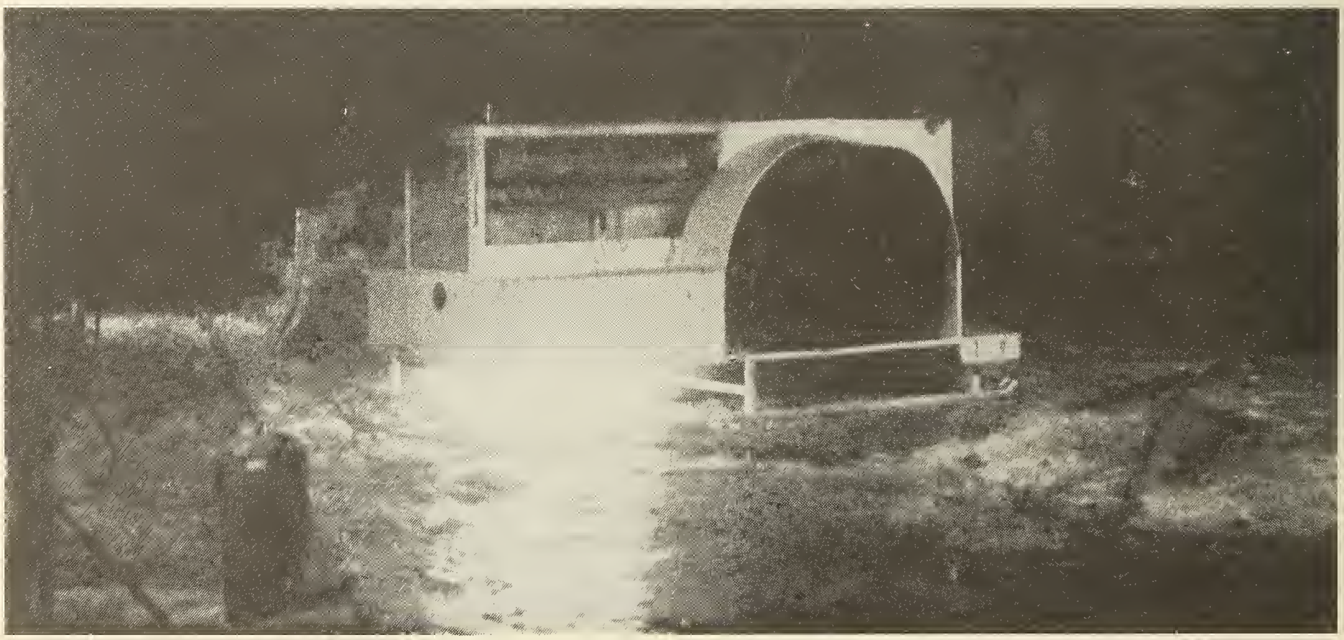

FIGURE 19.—Test fire burning under mockup.

FIGURE 20.—Twin-agent discharge onto test fire.

FIGURE 21.—Test fire fully extinguished.

STUDIES OF ALTERNATIVE SYSTEM DESIGNS

As noted previously, mines vary so widely in extraction methods, layout, ventilation plans, equipment selection, etc., that no single fueling area fire protection system design is universally applicable. Each fueling system needs to be individually analyzed for fire hazards and appropriate fire safety measures specified. However, the generic fire protection system design concepts developed through this research are intended to be flexible enough to adapt to a wide variety of conditions. In order to evaluate the applicability of these generic design concepts to a wide range of mine settings, a second fueling area fire protection system was installed in a high-back room-and-pillar lead mine in Missouri, and "paper studies" of other potential system configurations were performed. The second system has functioned properly for 16 months, and the paper-study results show that the generic design concepts can be applied to nearly any fueling system layout.

COST-EFFECTIVENESS ANALYSIS

The cost effectiveness of fire control systems can be analyzed in many ways. Two common approaches are to consider (1) the cost of the system versus the cost of potential fire losses and (2) cost-performance tradeoffs between various types and configurations of systems.

SYSTEM COST VERSUS FIRE COST

Numerous quantitative methods are available to assist risk managers in comparing the cost of various risk-management tools (e.g., a fire control system) to the cost of sustaining a particular loss (e.g., a fire). These quantitative methods require numerous inputs, but most important are estimates of (1) the probability of the occurrence of a particular loss and (2) the magnitude of potential losses.

Although the magnitude of potential losses is easily determined, an estimate of the probability of occurrence can require considerable effort. These estimates are generally based on industrywide long-term loss experiences or calculated using complex predictive techniques such as fault-tree analysis, failure modes and effects analysis, and criticality analysis.

Estimates of the probability of occurrence and magnitude of losses are combined to yield an "expected annual loss." Various risk-management tools such as insurance, coinsurance, hazard reduction, and installation of safety devices are then evaluated in light of the "expected loss." Other factors which are difficult to quantify, and therefore difficult to consider through quantitative methods—such as the potential for casualties and the need to maintain a certain production level—may also profoundly influence the development of a risk-management strategy. If the fire hazards analysis indicates that personnel safety may be threatened, precautions such as redesign of the fueling area and/or automatic fire protection system are appropriate, regardless of the outcome of any system-cost-versus-fire-cost analyses.

Since no large-scale fueling area fires have occurred, no industrywide loss experience exists, and a calculation of loss probabilities using a predictive technique is beyond the scope of this report. Thus, a case-study example illustrating these principles is not provided. However, even with mine shutdown costs of as little as $85,000 per day, a probability of the occurrence of fire as low as 0.3 pct/yr (the equivalent of one fire every 333 yr), and no other cost factors considered, a complete automatic fire sensing and suppression system would be an economically attractive loss-control option.

COST-PERFORMANCE TRADEOFFS BETWEEN SYSTEMS

The primary purpose of an underground fueling area fire sensing and suppression system is to reduce the safety hazard posed by a potential fueling area fire. Once the need for fire protection is established, however, an analysis of cost versus performance between various system options will permit selection of the most cost-effective approach to achieve the safety level desired.

Numerous techniques are available to measure cost effectiveness. The following example is provided to illustrate the application of one such method to a specific fueling system configuration.

Six types of fire protection systems are considered in this example: water, high-expansion foam, AFFF, Halon 1301, dry chemical, and twin agent. The analysis is based on an unenclosed fuel transfer area 65 ft long, 20 ft wide, and 13 ft high with moderate-to-high ventilation, with the following stipulations: Combustible-liquid spill fires as well as running-fuel and pressure fires could occur. No ordinary combustibles materials are stored in the area. All systems, except the water system, include cross-zones ultraviolet detection.

The cost-effectiveness analysis is accomplished in three steps as shown in table 6. First, each fire protection system is evaluated for effectiveness by assigning effectiveness points (Pt) from 0 to 800 for each evaluation criteria, multiplying the Pt value by a weighting factor (Wt) from 1 to 3, and summing the resulting ratings (Rt) for each evaluation criteria to yield a system effectiveness rating. Second, the cost of each type of system (including installation cost) is determined. Third, the system effectiveness rating is divided by the cost to yield a cost effectiveness index for each system.

The potential range of cost-effectiveness indexes for this example is 0 (no system effectiveness) to 1.41 (highest possible system effectiveness rating divided by lowest system cost). In this example, one system type, twin agent, has both the highest effectiveness rating and the highest cost-effectiveness index.

TABLE 6.—Cost-effectiveness matrix for fueling area fire protection systems

	System type								
	Water			High-expansion foam			AFFF		
	Pt	Wt	Rt	Pt	Wt	Rt	Pt	Wt	Rt
Evaluation criteria:									
Suppressant effectiveness for—									
Class B spill fire	200	3	600	300	3	900	800	3	2,400
Class B pressure fire	0	3	0	0	3	0	200	3	600
Class B running-fuel fire	0	3	0	200	3	600	300	3	900
Class A fire	500	1	500	300	1	300	800	1	800
Extinguishing time	100	2	200	400	2	800	400	2	800
Effects on personnel	400	1	400	300	1	300	400	1	400
System effectiveness rating	1,700			2,900			5,900		
System cost	$7,350			$10,900			$10,600		
Cost-effectiveness index	0.23			0.27			0.56		

	Halon 1301			Dry chemical			Twin agent		
	Pt	Wt	Rt	Pt	Wt	Rt	Pt	Wt	Rt
Evaluation criteria									
Suppressant effectiveness for—									
Class B spill fire	0	3	0	400	3	1,200	800	3	2,400
Class B pressure fire	0	3	0	400	3	1,200	800	3	2,400
Class B running-fuel fire	0	3	0	400	3	1,200	800	3	2,400
Class A fire	0	1	0	400	1	400	800	1	800
Extinguishing time	500	2	1,000	500	2	1,000	500	2	1,000
Effects on personnel	300	1	300	400	1	300	400	1	400
System effectiveness rating	1,300			5,300			9,400		
System cost	$10,300			$10,300			$16,500		
Cost-effectiveness index	0.13			0.51			0.57		

Pt Effectiveness points (0–800). Wt Weighting factor (1–3). Rt Resulting rating (Pt × Wt).

SUMMARY

In response to the growing fire safety hazard posed by underground fuel storage and fuel transfer areas, the Bureau has developed guidelines for safe and efficient fueling system designs, prepared specifications for automatic fire sensing and suppression systems for these areas, successfully conducted laboratory and in-mine fire tests of prototype systems, and conducted cost-effectiveness evaluations of various fueling area fire protection system designs.

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